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Impact of process parameters and heat treatment on mechanical properties of Ti64 LBM

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Abstract

Titanium is a very useful material for aerospace part manufacturing due to its mechanical properties and its lightness. Additive layer manufacturing (ALM), and amongst it Laser Beam Melting (LBM), is a new tool to manufacture parts that have a certain degree of complexity. It allows for the reducing of lead time, as well as reduces the development cycle. The aerospace industry is using more and more this tool to manufacture parts, either for development or for production.

With that in mind, Ti64 was developed in Vernon in order to manufacture parts for the Ariane propulsion engines. Certain parameters have been modified from the standard EOS set of parameters in order to gain in elongation at cryogenic temperatures. Also, a special work was performed in order to define the best heat treatment for Ariane’s applications.

The main parameters adjusted were linked to the baseplate temperature during building, as well as the use of HIP. The gain was not only on elongation, but also on porosity rate and mechanical properties (tensile, fatigue) at cryogenic temperatures. Other parameters are being studied today in order to increase productivity.

Introduction

Titanium is a very interesting material for aerospace applications. Its lightness, its specific mechanical properties on a large array of temperatures make it a go-to material [1].

Additive manufacturing is a recent tool for shaping and making parts, allowing for the fabrication of new shapes and the integration of new functions on parts. Furthermore, the lead time is consequently reduced, making it possible to start a development and having a qualified part in 15 month time.

The next step is, evidently, to match the two and develop the material for additive manufacturing applications. Samples for evaluating the mechanical properties at room temperature (300K) as well as cryogenic temperature (20K) were produced and tested.

Context and technical requirements

The context of our study is the development of a new material in Laser Powder Bed Fusion (L-PBF, also called LBM) for ArianeGroup applications. Our parts work at cryogenic temperature (around 20K, ie -253°C), and the whole characterization have to be performed at those temperatures. However, the cost of the tests at such temperatures is quite important (mostly due to the liquid Helium needed to cool down the samples) and a first evaluation of the material have been done at room temperature.

The cleanliness specifications require that no part create flying particles within the propulsion engine. ALM is known to produce parts with higher roughnesses than traditional processes, mostly due to unmelted powders, and to the layer by layer process. Even though finishing processes were in mind at the early stage of development, it was asked that the as-built roughness be reduced to a minimum.

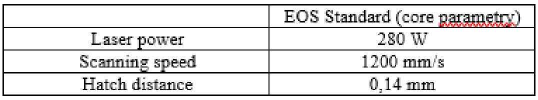
ALM processes tend to create a great amount of residual stresses. It is often seen during manufacturing that the part deforms and hit the recoater, leading to the scraping of the part or in the best case scenario to a pause in the process. Working on the geometry of the part was also envisioned in the next steps, but it was asked to reduce the stresses created during the process by working precisely on the process, in order to have more freedom in the geometries of the parts. This would also allow to reduce the risk of cracking of the parts, either during the printing or after.

Finally, ALM processes are known to have a greater amount of porosities compared to other processes like casting or powder metallurgy. Existing parametries at the time of the study led to less than 1% of porosity. However, due to the requirements in terms of critical defects in the final parts, the porosity levels were asked to be reduced to less than 0.1%.

Machine

All the development was performed on EOS M290 machines, with EOS standard set of parameters to start with. All powder was bought to EOS directly, according to their standard 15-45µ PSD specification. The main parameters are listed in Table 1.

Table 1: Standard EOS parametry for Ti64 LBM



	EOS Standard (core parametry)
Laser power	280 W
Scanning speed	1200 mm/s
Hatch distance	0,14 mm

Step by step

As stated earlier, the focus of this article is on the process improvements [2].

Layer Thickness

Today, ALM processes cannot allow for both high productivity and reduced surface roughness at the same time; a compromise has to be made. As it was the beginning of our works on titanium parts in ALM, it was decided to aim for the best surface roughness possible. Finishing processes (out of the scope of this article) were envisioned, but a good starting surface state was necessary.

Two parametries were available on the EOS M290 machine, with two different layer thicknesses: standard and improved. Obviously, the improved parametry would lead to an increased productivity. But the criteria to choose between these two starting parametries was the actual roughness on the fused material. Dedicated samples were built, with upskin and downskin zones as well as vertical areas. EOS certificates indicate the roughness expected on improved layer thickness should be better than the standard, but it only focuses on vertical walls. Our focus was made on the downskin areas, as they presented the highest roughnesses. standard layer thickness samples showed an average Ra of 11µm when the improved layer thickness samples had an average Ra of 13µm The angle of the downskin areas evaluated was 45°.

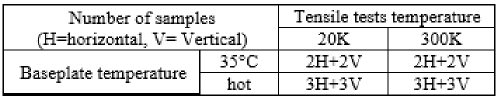
Our choice was thus made to use the standard parametry.

Baseplate Temperature

Although no cracks were seen so far in our development, the literature [6] mentioned that residual stress in ALM are important and may lead to cracking, either during the manufacturing of the parts or right after. It also mentions that residual stresses in Ti64 are greater than in Inconel 718 or in aluminum-based alloys [5][7][8]. These residual stresses are mostly caused by the great amount of energy focused by the laser on a localized area for a short time. This causes a high thermal gradient between the melt pool and the rest of already fused part. It was found that increasing the temperature of the baseplate lowers the thermal gradient thus reducing residual stresses in the final part [3].

We tested two different temperatures for the baseplate, the standard 35°C from the EOS set of parameters, and a hot temperature which was the highest temperature possible on the M290. After manufacturing, all samples were treated with heat treatment HT1 (temperature T1 for 2 hours), then machined. Table 2 list the number of samples used.

Table 2: Number of samples per baseplate temperature and tensile test temperature



Number of samples (H=horizontal, V= Vertical)		Tensile tests temperature	
		20K	300K
Baseplate temperature	35°C	2H+2V	2H+2V
	hot	3H+3V	3H+3V

Microstructures were really similar, regardless of the baseplate temperature chosen. Mechanical results are presented below.

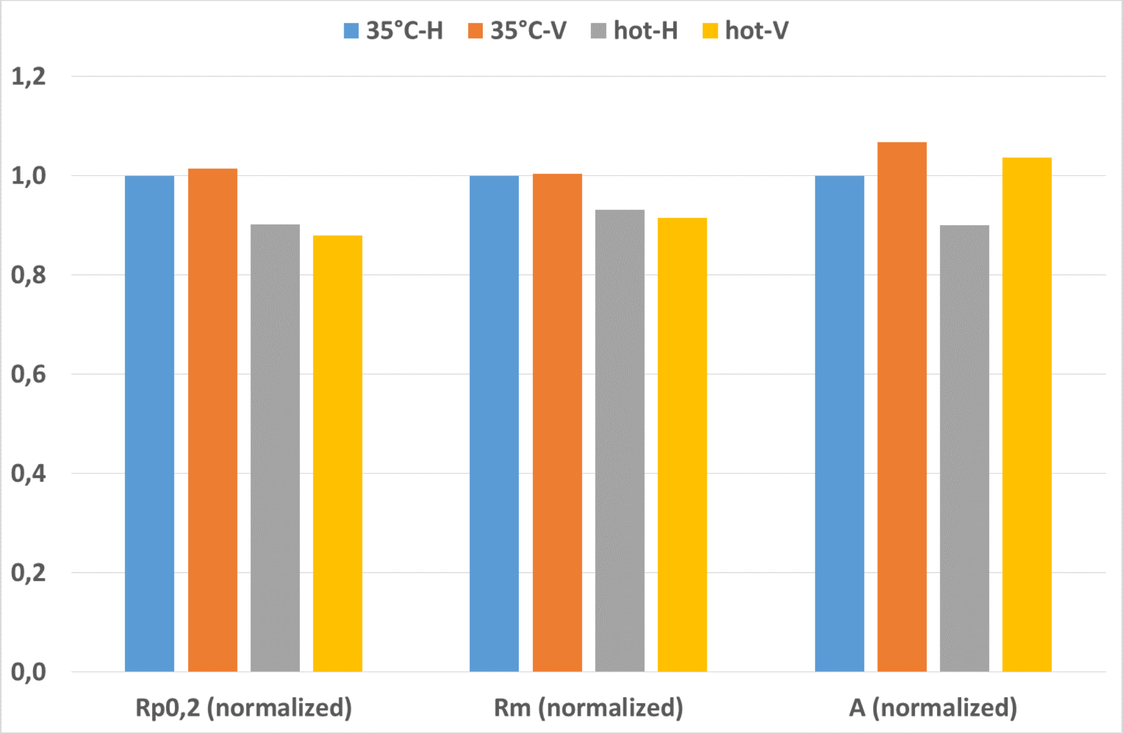


Figure 1: Tensile results at 300K depending on the baseplate temperature chosen

Figure 1 shows tensile results at 300K depending on the baseplate temperature. Values are averaged and normalized versus 35°C-V. No particular differences between the two baseplate temperatures are noticeable at room temperature.

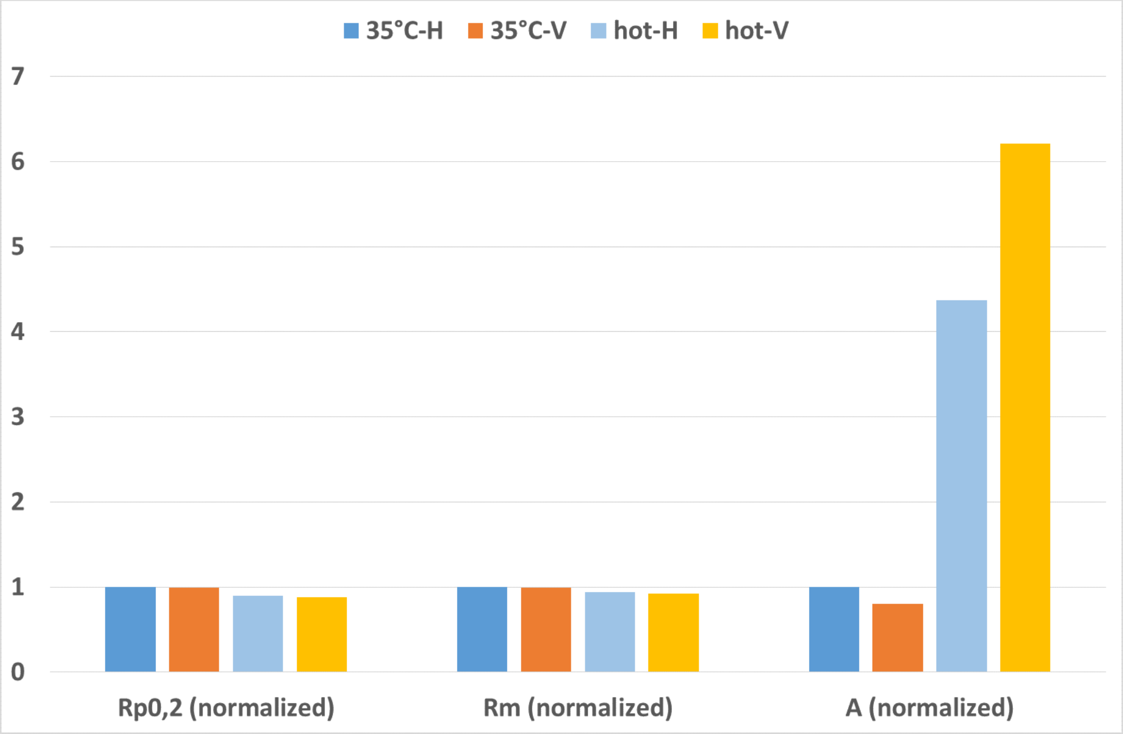
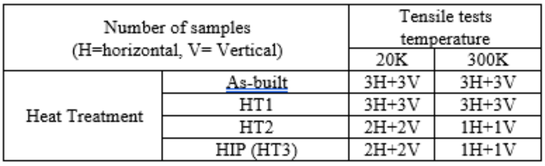


Figure 2: Tensile results at 20K depending on the baseplate temperature chosen

Figure 2 shows a higher elongation at 20K with a hot baseplate, multiplying by almost 6 the elongation. As cryogenic temperatures were our targeted operating conditions, the choice of a hot baseplate as standard was made.
This hot temperature (or higher temperatures if available) is now used [9] by many to produce titanium.

Heat Treatments and HIP
The specification in terms of critical defect require to have the lowest possible porosity. The idea was to test the influence of the Hot Isostatic Pressing (HIP) on the porosity rate. In the same time different standard Heat Treatments were tested, and a small design of experiment was performed to evaluate the mechanical properties at room and cryogenic temperature.
All samples were manufactured using a hot baseplate.
As expected, results showed that the porosity rate were reduced by a factor of 2 between hipped parts and non-hipped parts, on both the porosity rate and the max porosity size. This result was expected.
Mechanical results were more interesting. They revealed that the properties were modified more and more as the temperature of the heat treatment increased, and that the HIP could be considered as a formal HT and not only used to reduce the porosity levels.
In our test plan, we tested different temperatures HT1, HT2, HT3, each time for the same dwell time of 2 hours. HT1, HT2 and HT3 are in increasing order of temperature. HT3 was actually a HIP. Table 3 lists the number of tested samples.

Table 3: Number of samples per tensile test temperature and per heat treatment



Number of samples (H=horizontal, V= Vertical)		Tensile tests temperature	
		20K	300K
Heat Treatment	As-built	3H+3V	3H+3V
	HT1	3H+3V	3H+3V
	HT2	2H+2V	1H+1V
	HIP (HT3)	2H+2V	1H+1V

The ASTM dedicated to Ti64 ELI LBM [4] gives minimum properties at room Temperature (300K) for Ti64 ELI LBM as follows:

- Rp0,2 = 795 MPa
- Rm = 860 MPa
- Elongation = 10%.

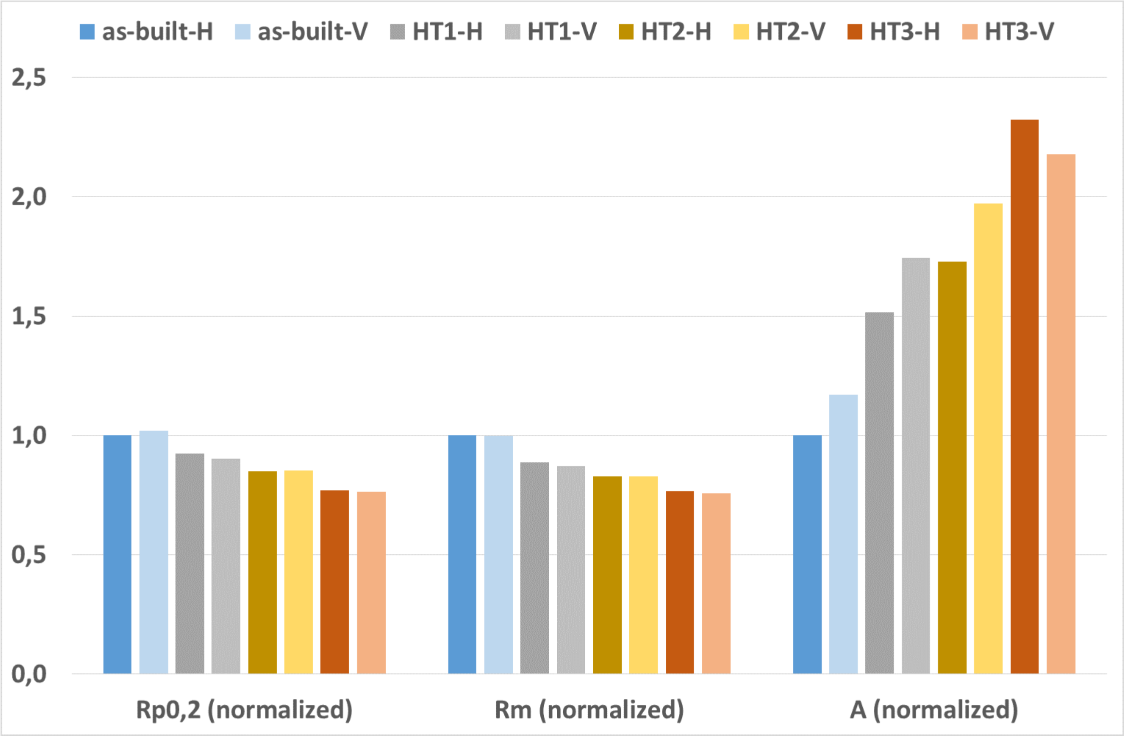


Figure 3: Tensile results at 300K depending on the Heat Treatment performed

All tested heat treatments allow for better mechanical properties than the minimum proposed by the ASTM. Figure 3 presents tensile results at 300K, averaged and normalized values versus as-built-H. It also reveals that a heat treatment is mandatory to achieve a certain elongation rate, and that elongation increases with the temperature of the heat treatment. The change of better orientation for elongation (H better than V with HIP compared to V better than H with other heat treatment) is most certainly caused by the low amount of tests performed, and does not represent properly the behavior of the material. This result is not seen at 20K.

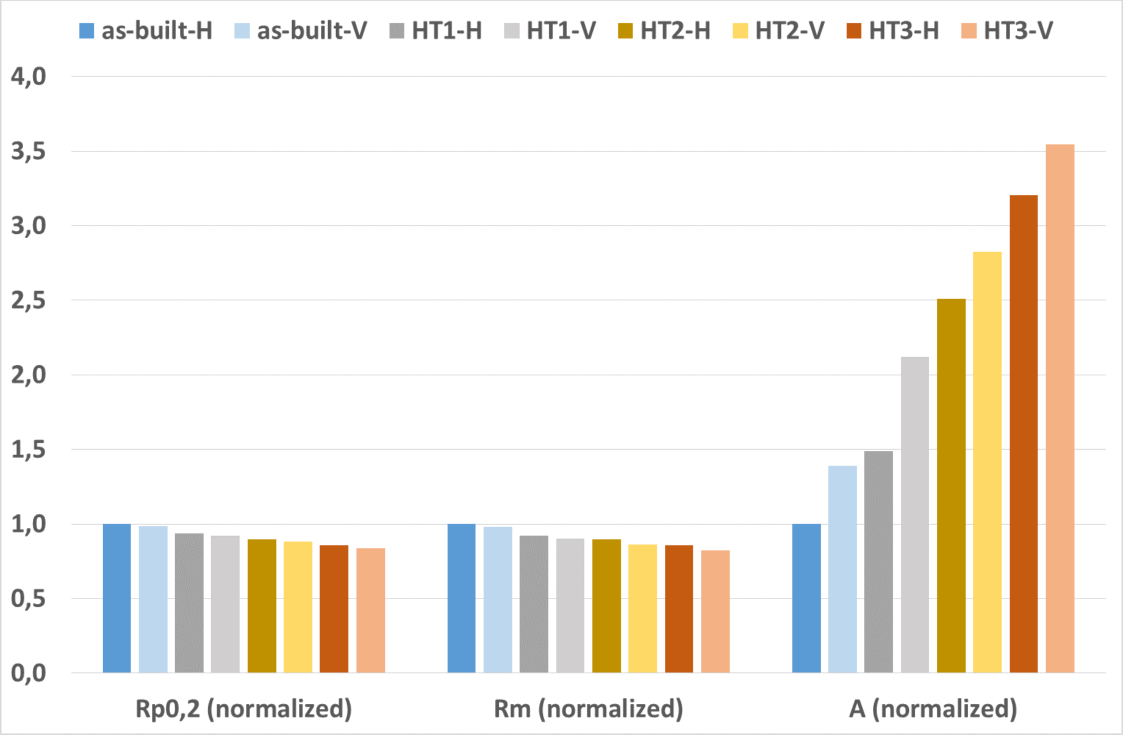


Figure 4: Tensile results at 20K depending on the Heat Treatment performed

Figure 4 presents results quite similar to Figure 3. It was found that increasing the temperature of the heat treatment (no HT, HT1, HT2, HT3 = HIP) leads to increasing elongation at 20K as well as reducing Rp0,2 and Rm. Anisotropy cannot be completely erased.
Microstructures were here again really similar, regardless of heat treatment. A more thorough examination of the dendrites dimensions and their orientation may lead to understand better the differences seen on the mechanical properties.

Conclusion

Choice and improvements were done on the standard EOS set of parameters to manufacture LBM Ti64. These choices and modifications (mostly layer thickness and baseplate temperature) allowed for an increased quality of the material, and improved mechanical properties at the targeted operating conditions. Some of these improvements are now used worldwide, mostly because they were the most sensible idea.
Other improvements can be performed on other parameters, now that the maturity of this process has increased.

References

[1] On the characteristics of titanium alloys for the aircraft applications, Materials Today: Proceedings 4 (2017) 8971–8982, P. Singh, H. Pungotra, N. S. Kalsi
[2] Optimisation of process parameters to address fundamental challenges during selective laser melting of Ti-6Al-4V: A review, International Journal of Machine Tools and Manufacture, Volume 128, May 2018, Pages 1-20 H. Shipley, D. McDonnell, M. Culleton, R. Coull, D. Trimble
[3] In-situ residual stress reduction, martensitic decomposition and mechanical properties enhancement through high temperature powder bed pre-heating of Selective Laser Melted Ti6Al4V, Materials Science and Engineering: A, Volume 695, 17 May 2017, Pages 211-220, Haider Ali, Le Ma, Hassan Ghadbeigi, Kamran Mumtaz
[4] ASTM_F3001_2014 Standard Specification for Additive Manufacturing Ti64 ELI with Powder Bed Fusion
[5] An experimental study of residual stress and direction-dependence of fatigue crack growth behaviour in as-built and stress-relieved

selective-laser-melted Ti6Al4V, Materials Science and Engineering: A, In press, accepted manuscript, Available online 6 April 2019, Abdul Khadar Syed, Bilal Ahmad, Hua Guo, Thays Machry, Xiang Zhang

[6] An overview of residual stresses in metal powder bed fusion, Additive Manufacturing, Volume 27, May 2019, Pages 131-149, Jamison L. Bartlett, Xiaodong Li

[7] Study on the microstructure, mechanical property and residual stress of SLM Inconel-718 alloy manufactured by differing island scanning strategy, Optics & Laser Technology, Volume 75, December 2015, Pages 197-206, Yanjin Lu, Songquan Wu, Yiliang Gan, Tingting Huang, Jinxin Lin

[8] Experimental Analysis of Residual Stresses on AlSi10Mg Parts Produced by Means of Selective Laser Melting (SLM), Procedia CIRP, Volume 62, 2017, Pages 458-463, Alessandro Salmi, Eleonora Atzeni, Luca Iuliano, Manuela Galati

[9] Application of base plate preheating during selective laser melting, Procedia CIRP, Volume 74, 2018, Pages 5-11, R. Mertens, S. Dadbakhsh, J. Van Humbeeck, J. -P. Kruth